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Dynamic Modeling of Flood Management Policies

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Abstract

Economic and social impacts related to flood disaster are two important and interdependent issues addressed by flood management policies. Economic impacts include structural and non-structural damages caused by the floods and the social impacts of flood disaster are mainly related to evacuation, where public response to disaster warning plays an important role. This paper presents a system dynamics model that captures dynamic interaction between different components of the flood management system. The model provides a platform for evaluation of the consequences of various policy alternatives for flood management. The operation of reservoir and floodway has been simulated. Operating rules are developed for high flow/flood years to minimize flooding. Alternative operating rules are explored by changing reservoir storage allocation and outflows. Impacts on the flood management capacity of the reservoir are investigated by simulating gated spillway in addition to an existing unregulated spillway. Flood damages to buildings and infrastructure are calculated. Sensitivity analysis is performed on the reservoir levels at the start of the flood season and outflow from the reservoir. The modeling work on economic impacts of flood management policies is complete. However, the work on social aspects of flood management especially public response to flood warning and people's perception of risk with special relevance to evacuation planning is in progress. The model is implemented for the Red River basin in Canada using recorded data of large flood events.

Introduction

Floodplains provide advantageous locations for urban and agricultural development. Unfortunately, the same rivers that attract development periodically overflow their banks causing loss of life and property. Flood management is aimed at reducing potential harmful impact of floods on people, environment and economy of the region. Flood management process can be divided into three major stages: (a) planning; (b) flood emergency management; and (c) post flood recovery. During the planning stage, different alternative measures (structural and nonstructural) are analyzed and compared for possible implementation to reduce flood damages in the region. Flood management includes regular appraisal of the current flood situation and daily operation of flood control works. From the appraisal of the current situation decisions are made about evacuation and re-population of different areas. Post flood recovery involves decisions regarding return to the normal life. Issues of main concern during this stage of the flood management process include evaluation of damages, rehabilitation of damaged properties and provision of flood assistance to flood victims.

Operation of flood control works (reservoirs and floodways) in the river basin is an important aspect of overall flood management policy. The application of systems analysis techniques for operation of flood management structures has been an active area of research in water resources engineering. Most of the systems analysis techniques developed for reservoir operations are described in textbooks e.g. Loucks et al. (1981) and Mays and Tung (1992). Yeh (1985) reviewed various approaches to reservoir simulation and noted that despite considerable progress, the research related to reservoir system analysis has problems finding its way into practice. He attributed this partly to the fact that operators usually have not been involved in the formulation and development of computer models; partly to the fact that most applications deal with simplified reservoir systems and are difficult to adapt to real systems; and partly to institutional constraints.

The review of literature suggests that there is a strong need to explore simulation tools that can represent the complex systems in a realistic way and where operators can be involved in model development to increase their confidence in the modeling process. A promising alternative is system dynamics (SD) that compared to traditional systems analysis techniques does not require complex mathematical description of the system. System dynamics, a feedback based simulation approach, has a long history as a modeling paradigm with its origin in the work of Forrester (1961), who developed the subject to provide an understanding of strategic problems in complex dynamic systems. System dynamics is becoming increasingly popular for modeling water resource systems. Costanza et. al. (1990) has modeled coastal landscape dynamics using SD approach. Palmer and colleagues (1993, 1994, and 1995) have done extensive work in river basin planning using SD. Keyes and Palmer (1993) used SD simulation model for drought studies. Matthias and Frederick (1994) have used SD techniques to model sea-level rise in a coastal area. Fletcher (1998) has used system dynamics as a decision support tool for the management of scarce water resources. Simonovic et al. (1997) and Simonovic and Fahmy (1999) have used the SD approach for long term water resources planning and policy analysis for the Nile River basin in Egypt. Ford (1999) has described several system dynamics models of environmental systems. Ahmad and Simonovic (2000) have modeled reservoir operations for flood management using system dynamics.

The work reported in this paper is built on the previous work of Ahmad and Simonovic (2000). In earlier work they modeled the operation of a single multipurpose reservoir on a river for flood management. Current work includes the modeling of integrated operation of reservoir, diversion structure and floodway for a system of two rivers, where floods in one river influence the flows in the other river. Additionally, flood damage to buildings and infrastructure is calculated in this work.

This paper outlines a framework for modeling flood management policies using the SD approach. The focus of research is on modeling operation of flood control structures and calculation of damages caused by floods. A general approach for modeling operation of reservoir, diversion structure and floodway is presented by introducing model structure and complex relationships among its components. Reservoir operating rules have been developed for high flow years to minimize flooding. Impacts on flood management capacity of reservoir have been explored by simulating a gated spillway in addition to an existing unregulated spillway. Alternative operating rules have been investigated for floodway and reservoir by changing reservoir storage allocation, reservoir levels at the start of flooding season and outflows. The benefits of the proposed approach are demonstrated by application to a case study of Red River Basin in Canada. Finally, a discussion of results is presented with conclusions. Suggestions for possible model application and extension conclude the paper.

System Representation

The SD model is developed for flood management policy analysis. Developed model is used to formulate a reservoir, diversion and floodway operational policy for high flow years to minimize flooding. The model also serves as a tool for studying impacts of changing reservoir storage allocation, temporal distribution of reservoir levels and outflows, and capacity of floodway. The general architecture of the model is presented in this section and discussion of model sectors and complex dynamic relationships follow.

The control structures in river basin play an important role in managing floods and reducing the damages caused by them. Reservoirs, diversions and floodways are commonly used flood control structures. Reservoirs store water and reduce peak flows in rivers. Reservoirs can also be used to alter the timing of flood peaks. Diversion structures are used to divert water from the river thus reducing the peak discharge. Usually diverted water is taken out of the system by disposing it to a near by water body (lake or sea). Floodways are used to by-pass a town or important structures. A part of flow is taken out of river to by-pass a town and is then brought back into the river system, thus reducing the flow and damages at by-pass point. Due to the modular nature of the simulation tool, the model is developed in sectors. A general simulation model for flood management policy analysis can be divided into several main sectors, i.e., reservoir, diversion, floodway, and damages. Details on these sectors follow.

1. Reservoir

This is the core sector of the model. Inflows and outflows from the reservoir are the main components of this sector. Flow from all tributaries directly contributing to the reservoir is considered as inflow to the system. Inflow data files are provided to the model as input. Total reservoir outflow consists of reservoir releases through conduit, spill, and evaporation and seepage losses. Conduit flow and spillway modules govern the flow through the conduit and the spillway, respectively. System constraints, spillway curves, and conduit outflow capacity at different gate openings are provided to the model. Reservoir operating rules are captured in this sector using IF-THEN-ELSE statements. A screen dump of the reservoir sector is shown in Figure 1. The reservoir sector can be further subdivided into two more sectors i.e. upstream and downstream. Upstream sector calculates the area flooded upstream of the reservoir. Upstream flooding is triggered by a combination of reservoir inflow, reservoir level, and reservoir outflow. The number of days when the upstream area is flooded is also counted in this sector. Downstream sector calculates individual and total flooded area and duration of flooding due to the reservoir operation at selected locations between the reservoir and final disposal point of the river.

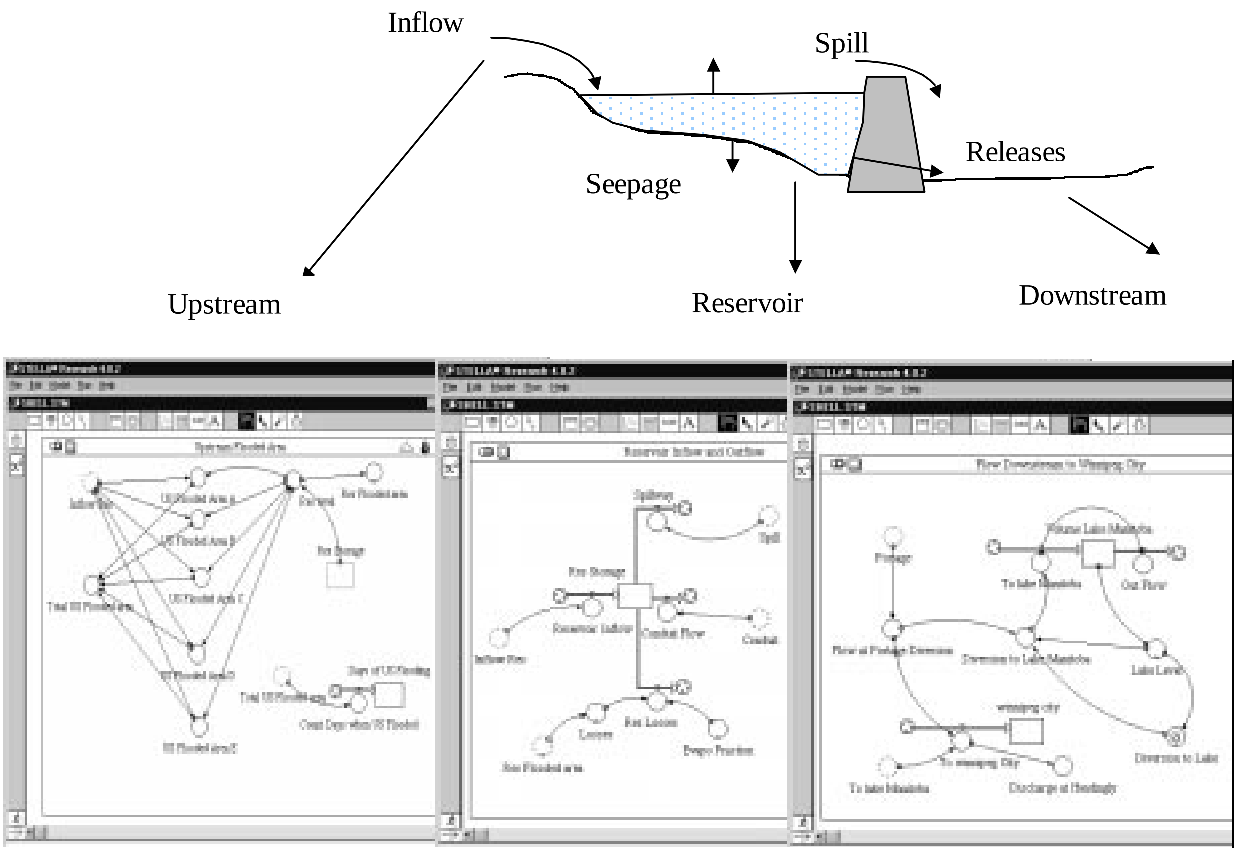


Fig.1 Screen dump of the reservoir sectors (adopted from Ahmad and Simonovic 2000).

2. Floodway

This is another important sector of the model. This sector controls the flow that is diverted from the main river to by-pass an area to be protected from floods. System constraints, floodway curves, and flow capacity are required information to setup this sector. Floodway operating rules are captured in this sector using IF-THEN-ELSE statements.

3. Damages

This sector is used to calculate damages to buildings and infrastructure caused by floods. Stage-damage curves are the main information required to setup this sector. Input includes number of buildings flooded, length of roads inundated and depth of flooding.

To set up a general simulation model for flood management inflows, system constraints and operating rules are required. Additional data might be required depending on specific objectives of the study. The data requirements for this study are discussed in detail in the following section. As output, model provides information on variation of the reservoir levels, area flooded due to operation of flood control structures, and duration of flooding. The model also calculates flood damages. Once all sectors are developed and model relationships and operating rules are defined, the user can run the simulation and evaluate the impacts of alternate operating rules. To demonstrate the applicability of the proposed modeling approach for flood management policy analysis, a case study is presented.

Case Study Application

With approximately 1.25 million inhabitants in the Red River basin in USA and Canada, the basin is highly productive agricultural area serving local, regional and international food needs. Several devastating floods have occurred in the valley during this century, causing damages to business and property worth millions of dollars. The latest flood event in 1997 clearly emphasized the need for comprehensive flood management in the basin using state of the art modeling tools. The proposed SD approach for modeling flood management policies has been applied to the Red River Basin in Canada (Figure 2). Situated in the geographic center of North America, the Red River originates in Minnesota and flows north. It forms the boundary between North Dakota and Minnesota and enters Canada at Emerson, Manitoba. It continues northward to Lake Winnipeg. The Red River basin covers 116,500 km^2 of which nearly 103,500 km^2 are in the United States and the remaining 13,000 km^2 are in Canada. The basin is remarkably flat. The slope of the river is on average less than 9.5 cm per kilometer. During the major floods the entire basin becomes the floodplain. The Red River Basin has a sub-humid to humid continental climate with moderately warm summers, cold winters, and rapid changes in daily weather patterns. The earliest recorded flood in the basin was in 1826, the largest on record. All other floods were exceeded by the 1997 event.

Most of the flood management in Canadian portion of the Red River Basin was initiated after the 1950 flood. The current flood control works for the Red River basin consist of the Red River Floodway, the Portage Diversion and the Shellmouth Reservoir on the Assiniboine River, the primary diking system within the City of Winnipeg, and community diking in the Red River basin. Following the 1950 flood on the Red River, a commission was set up (Royal Commission, 1958) that recommended the construction of the Red River Floodway (completed in 1966), the Portage Diversion (completed in 1970) and the Shellmouth Reservoir (completed in 1972). In early 1970s a series of ring dikes around communities in the Red River Basin were also constructed.

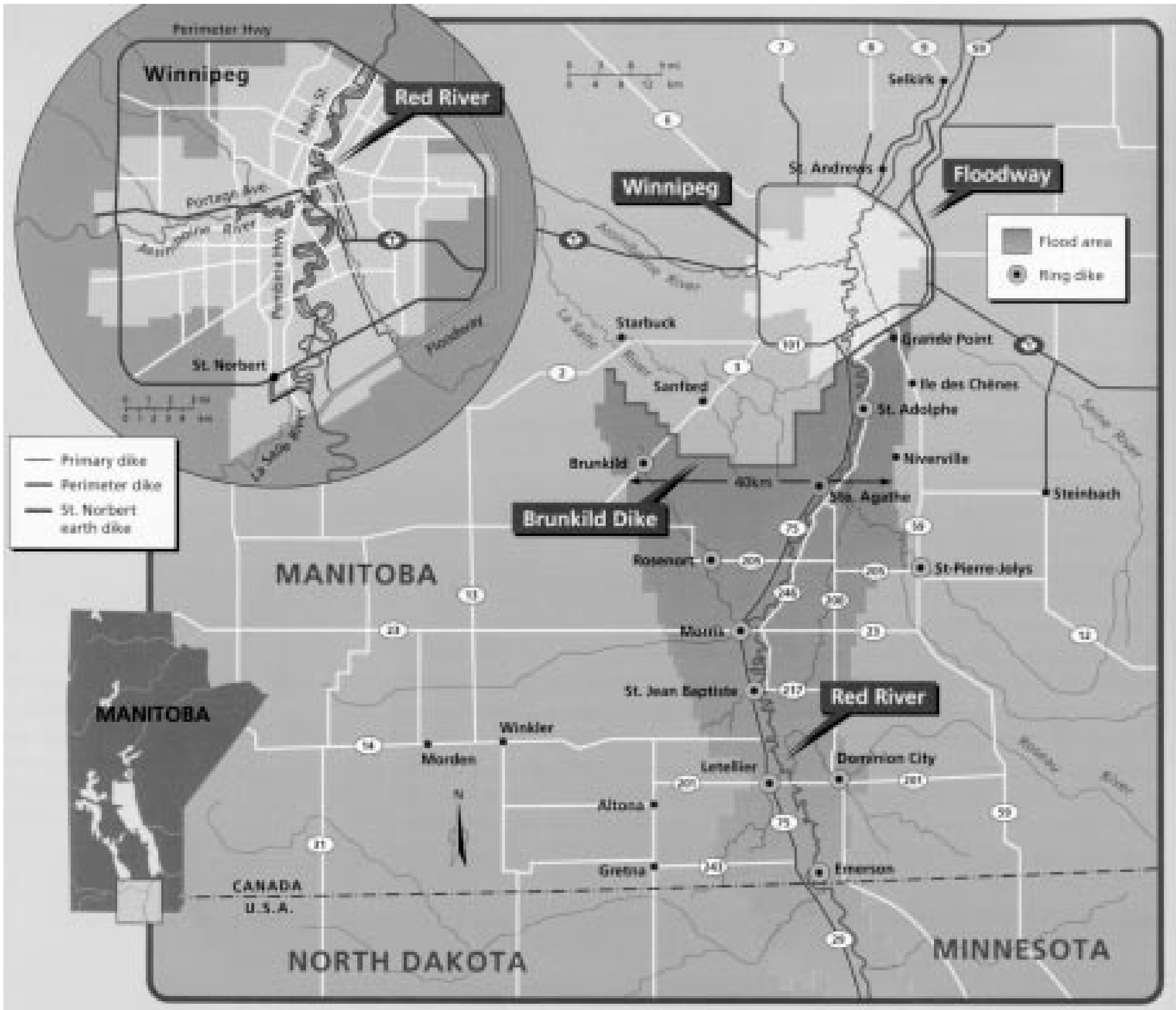


Fig. 2 Study area

The main flood control components of the system modeled in this study are the Shellmouth Reservoir, Portage Diversion and Red River floodway. Shellmouth Reservoir is located on the Assiniboine River, close to Manitoba/Saskatchewan border in Canada. The Shellmouth dam and reservoir were developed primarily to protect the cities of Brandon and Winnipeg from floods on the Assiniboine River. Supplementary benefits of the project include flood control to agricultural land in the river valley. Currently, there is no control structure on the spillway to regulate spill from the Shellmouth Reservoir. The Portage Diversion was constructed to divert the water in the Assiniboine River to Lake Manitoba. The Red River floodway was constructed to reduce flooding in the Winnnipeg City by diverting water from the Red River. Considering these aspects of flooding and importance of flood control structures in the basin the objectives of the simulation modeling study were defined to:

- Develop a reservoir operating policy for high flow years to minimize flooding.

- Develop floodway operating rules for high flow years to minimize flooding.

- Explore the impacts on the reservoir flood management capacity by installing gates on an existing unregulated spillway.

- Develop a tool for evaluating alternative operating rules by changing the reservoir storage allocation, reservoir levels at the start of the flood season and the reservoir outflows.

- Identify the additional floodway capacity to accommodate the largest recorded flood of 1826.

A schematic diagram of flood control structures in the study area is shown in Figure. 3. The Assiniboine River, on which the Shellmouth Reservoir is located joins the Red River in Winnipeg. Thus, flooding on the Assiniboine also contributes towards flooding of the Winnipeg City. At Portage, a portion of the Assiniboine River discharge can be diverted to Lake Manitoba through a diversion channel of capacity 710 m^3/s.

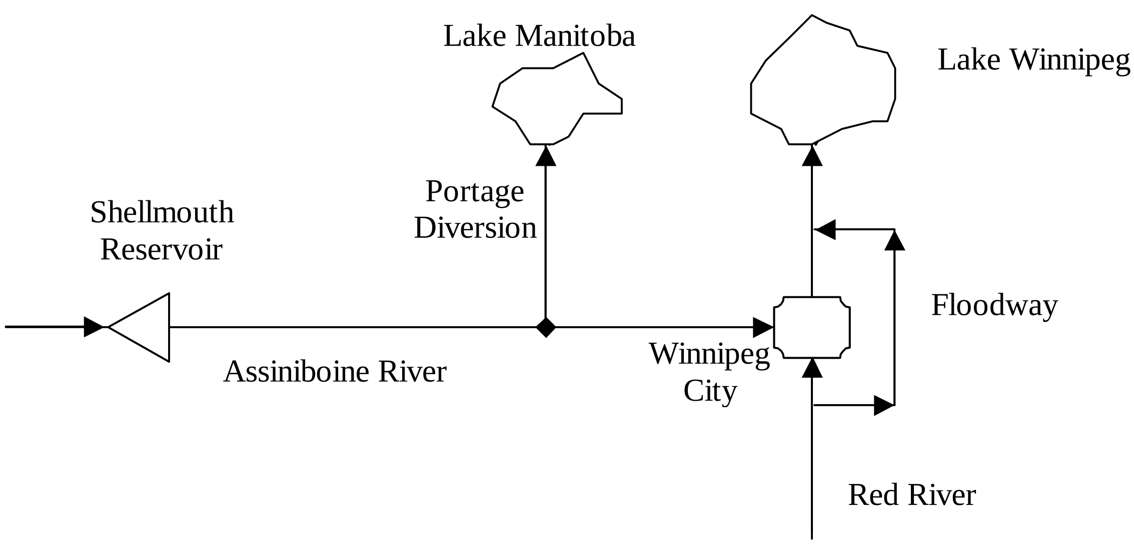


Fig. 3 Schematic diagram of the flood control system in the study area

The Shellmouth Dam is 1319 m long and 19.8 m high zoned earth-fill embankment A gated concrete conduit with discharge capacity of 198.2 m^3/s on the east abutment and a concrete chute spillway on the west abutment control outflow from the dam (Water Resources Branch 1992). The reservoir is 56 km in length, 1.28 km in average width and covers a surface area of 61 km^2 when full. The elevation of top of the dam is 435 m above mean sea level with a dead storage elevation of 417 m. The spillway elevation is 12 m higher, at 429 m. The volume of inactive pool below the conduit invert elevation is 12.3 x 10^6 m^3. The difference between volume of reservoir at active storage (370 x 10^6 m^3) and crest level of natural spillway (477 x 10^6 m^3) is flood storage capacity of reservoir i.e. 107 x 10^6 m^3. Current operating rules specify that the reservoir should be brought to 185 x 10^6 m^3 by March 31 to accommodate floods and a reservoir volume of 370 x 10^6 m^3 is a goal during the summer months. Maximum reservoir outflow is limited to 42.5 m^3/s

to prevent flooding downstream and the outflow must be greater than 0.71 m^3/s to avoid damage to fish and aquatic life in the river system (Water Resources Branch 1995).

The data that were used to set up the model include: (1) reservoir volume curve; (2) reservoir area curve; (3) reservoir inflow (daily); (4) reservoir water levels (daily); (5) reservoir operating rules; (6) spillway rating curve; (7) conduit rating curve; (8) relationship between depth of water and area flooded at all points of interest in the basin; (9) evaporation and seepage losses from the reservoir, (10) spillway operating curves; (11) stage-damage curves; and (12) river inflows (daily).

Modeling Strategy

The modeling process starts with the definition of its purpose/goal. Then boundaries of the system to be modeled are specified. This is followed by identification of key variables that affect the system behavior the most. Then the system structure is described, the stocks and flows are identified and system structure is mapped in the modeling tool using basic building blocks. Quantitative information i.e. equations and data is included in the model structure. The model is run to test the behavior. The model is evaluated and adjustments are made. Once the model is replicating system behavior satisfactorily it is ready for simulation analysis.

The main objective of the study was to develop a flood management policy for high flow years/floods. The five largest flood events in the history of the Shellmouth Reservoir, occurring in 1974, 1975, 1976, 1979, and 1995, were selected for simulation. Only inflow was considered as input to the reservoir. Contribution of rain over the reservoir was not taken into account considering its insignificant influence on the reservoir operation during a flood. Outflow through conduit and spills were considered as total outflow from the reservoir. Similarly, five largest flood events in the Red River, occurring in 1966, 1969, 1979, 1996, and 1997 were selected for simulation. Additionally, the largest recorded flood event in the Red River in 1826 was also simulated. The Assiniboine and the Red Rivers join there flows in the Winnipeg City. Historic data reveals that the worst floods on both rivers have occurred in different years, so far. Using the simulation approach presented in this study a worst possible flooding scenario can be modeled by simulating the maximum recorded floods in the history of both rivers and then combining the flows in the Winnipeg City.

The simulation model presented in this paper has been implemented in the *STELLA* environment (High Performance Systems Inc., 1992). The model was developed in different sectors i.e. reservoir, floodway, damages etc. as described in general model architecture. After defining connections between model sectors and components, operating rules were incorporated in the model using logical statements of IF-THEN-ELSE structure:

IF (Res_level>429.3) AND (Spillway_Control = 0) AND (TIME >120) AND
(Reservoir_Inflow>Unregulated_Spillway) THEN (198) (1)

This statement explains that if the reservoir is full (429.3 m), unregulated spillway is selected for simulation, it is flooding season (May), and inflow is more than outflow through unregulated spillway then conduit must be operated at its maximum discharge capacity (198 m^3/s). Similarly, if for simulation, a gated spillway option is selected and the reservoir level has reached between 430.5 m to 431.2 m and it is flooding season (late April to middle of June) then outflow should be equal to the inflow to the reservoir.

IF (Spillway_Control = 1) AND (Res_level >= 430.5) AND (Res_level <= 431.2) AND (TIME>110) AND (TIME <165) THEN (Reservoir_Inflow) (2)

Similarly, the next rule (3) states that no flow will pass through the floodway if floodway gates are close. Similarly, if the flow in Red River is less than or equal to the safe carrying capacity of river (1400 m^3/s) there will be no diversion through the floodway. When floodway gates are open and flow in the Red River is more than the safe carrying capacity of river then excess flow will be diverted to floodway up to a maximum of floodway capacity (1850 m^3/s).

IF (Floodway_Diversion_Control = 0) THEN (0) ELSE IF (Red_Floodway_up<=1400) THEN (0) ELSE IF (Floodway_Diversion_Control = 1) AND (Red_Floodway_up >= 1400) THEN MIN ((Red_Floodway_up-1400), (1850)) ELSE (0) (3)

Option is provided in the model to route floods through the reservoir using natural spill or gated spill scenarios. The model uses spillway rating curve and information on current reservoir level, inflows, and time of the year to make decision about discharges through spillway. The conduit flow module defines the flow through gated conduit. Based on which spillway option is active, there are two different sets of operating rules for conduit flow. Once spillway selection is made, this information is automatically passed to conduit control and appropriate conduit operating rules are fired. Current reservoir level, inflows, time of the year and safe channel capacity downstream of the reservoir are criteria on which quantity of the releases through conduit is based. At Portage a part of the Assiniboine River flow can be diverted to Lake Manitoba; this diversion is a function of flow in the Assiniboine river and capacity of the diversion channel. The flow in the Red River is diverted through floodway to protect Winnipeg City. This diversion is function of flow in the river, capacity of the floodway and water levels at the confluence of Red and Assiniboine Rivers in the Winnipeg City (St. James Bridge). The model using damage curves calculates damages to different categories of buildings and infrastructure.

Model Application

Model's main control screen to run the flood management simulations is shown in Figure 4. There are five separate input data files for the five largest floods on the Assiniboine and the Red River, respectively. User can select the flood year for simulation using a graphical tool (slider). Choices on the slider correspond to different flood years. Spillway module has a slider that provides user with an option to choose either unregulated or gated spillway for simulation. Similarly, user can choose to open and close gates of the Red River floodway for simulation. Slider is available to choose Shellmouth reservoir level at the start of simulation. Warnings linked to minimum and maximum reservoir levels have been provided in the model in the form of text messages and sounds. A text message "s*pillway will start operating soon*" prompts user when the reservoir level reaches the spillway crest level. A sound warning in the model is activated when the reservoir reaches the minimum or the maximum level. While simulation is running, the operator has control over the flow through conduit and can increase or decrease the discharges as the need arises. As output, the model provides information on variation of the Shellmouth reservoir levels and combined discharges at the confluence of the Red and the Assiniboine Rivers. The model also calculates the number of days when the reservoir is full or at the minimum level, and the number of days spillway is operated. Other model output includes the number of days of downstream/upstream flooding and the number of days when channel capacity is exceeded due to reservoir operation. The model also calculates total and individual areas flooded at several locations along the river due to the reservoir operation. Additional model output includes calculation of damages to buildings and infrastructure caused by flood. For calculation of damages the information that needs to be provided to the model includes, depth of water in the floodplain, number and type of buildings flooded, and length of roads inundated. This information comes from hydrodynamic model and GIS. The simulation model also calculates cost of building a dike to protect buildings from floods.

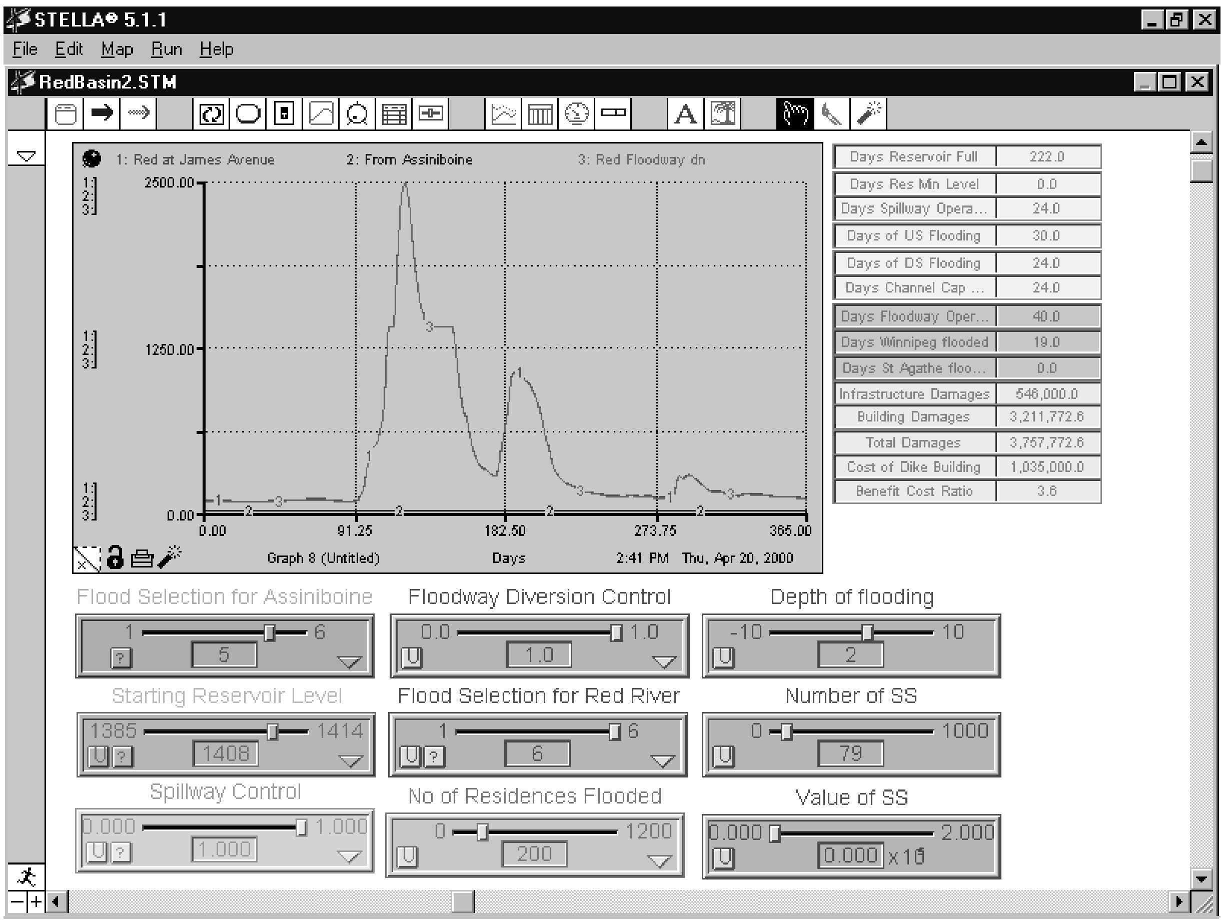


Fig. 4 Control screen of simulation model

After model development and calibration, several model runs were carried out. Following each run, the reservoir levels and area flooded due to the reservoir operation were carefully studied. Then modifications of reservoir operating rules were made to improve the reservoir performance in flood damage reduction. The calculation of the flooded area and duration of flooding due to the reservoir operation provides information on effectiveness of different operating policies for flood management. Simulation techniques are not capable of generating directly an optimal solution to a reservoir operation problem; however, by going through several runs of a model with alternative policies, near optimal operating policy can be identified.

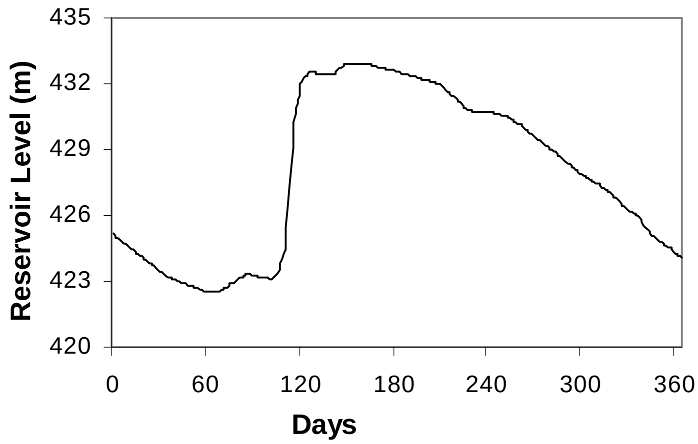
Simulations of the Shellmouth Reservoir operation were made for the five largest historic floods with natural and gated spill scenarios. Model inputs were annual series of daily inflows to the reservoir during the five major flood events. Model output includes daily variation of the reservoir level, daily discharges from the reservoir, total flooded area upstream of the reservoir, discharges and flooded area at seven downstream locations, and diversion to the Lake Manitoba at Portage. Contribution of the Assiniboine River towards the flooding of the Winnipeg City was studied. Policy alternatives were explored by changing initial reservoir storage level at the beginning of flood season. Similarly, simulation of the Red River floodway operation was carried out. Annual series of daily flows at Ste. Agathe were used as input to the model. Stage-damage curves were captured in the model. The data on number of buildings flooded and length of roads inundated in the vicinity of Ste. Agathe town due to 1997 and 1826 flood events was obtained from a study done by the KGS group (2000). For calculation of damages, buildings were divided into three main categories i.e. residential, agricultural, commercial. Total damages are sum of building and infrastructure damages. Model output includes: combined Red River and Assiniboine discharges at St. James; damages due to floods in the Ste. Agathe area; and number of days when floodway was operated. Model also calculates the additional floodway capacity required for safely diverting flood event of 1826. Time step of one day was used for simulation. Delay function was used for flood routing to capture the timing of flooding at downstream locations.

Results and Discussion

Daily variation of the Shellmouth Reservoir level for 1995 is shown in Figure 5. Summary of selected results is provided in Tables 1, and 2. Revised operating rules with natural spill and gated spill are shown in Figure 6 along with existing operating rules. Results show that with revised operating rules it was possible to operate the reservoir with only minor upstream and downstream flooding for four out of five major flood events. During the simulation of flood year 1975 and 1976 on the Assiniboine river, spillway was not operated and there was no flooding. In flood year 1974 the spillway was operated for only five days with maximum discharge of 9.35 m^3/s and 70 hectares were flooded. Similarly in 1979 the spillway was operated with maximum discharge of 37.97 m^3/s and 151 hectare of land were flooded. Simulations were made again for flood events of 1974 and 1979 with gated spillway option and it was found that downstream flooding can easily be avoided without increasing flooding upstream of the reservoir.

The flood on the Assiniboine in 1995 has a return period of 100 years and inflows were well over three times the volume usually experienced. However, this flood event provided an opportunity to look into the advantage of having a gated spillway. With the free spill option, 166 hectares upstream and 21,371 hectares downstream were flooded for 5 and 38 days, respectively (Table 1). Peak discharge was reduced from natural 660.92 m^3/s to 359.45 m^3/s through the reservoir operation. By routing the flood of 1995 through the reservoir with the gated spillway option there was a reduction of about 5,000 hectares in flooded area and flood days were reduced to 23.

Maximum outflow was reduced to 223.85 m^3/s, almost 40 % improvement over the unregulated spillway option. With gated spillway the maximum downstream discharge of the Portage diversion was 5.66 m^3/s which is equal to the minimum required flow as compared to 172.2 m^3/s with the free spill option. This means that Assiniboine River's contribution towards flooding of the Winnipeg City was negligible.



.Fig. 5. Shellmouth Reservoir daily variation of water levels for 1995 flood

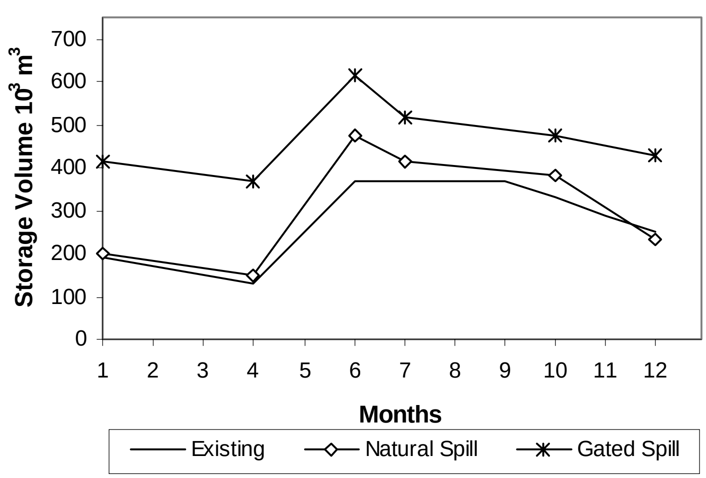


Fig. 6. Revised operating rules for Shellmouth Reservoir

The 1976 flood year was selected to investigate how initial water levels in the reservoir, at the start of flood season, affect the spillway operation and the reservoir levels during the flood. 1976 was selected because this year was the 2nd largest flood in terms of volume of inflow and the spillway was not operated during the simulation with free spill option. The simulations considered a range of reservoir levels between empty (422.5 m) and full (429.5) reservoir. Release rules are written in a way that they adjust outflow based on the information on inflow, time of the year, and the reservoir level. It was found that the impact of initial reservoir level on the reservoir levels during the flood is significant. As flood arrives soon after simulation starts, there is not enough time to bring the reservoir to a lower level to accommodate incoming flood. By increasing the initial reservoir level, the number of days when the reservoir is full, the number of days of upstream and downstream flooding and flooded area are increasing as well (Table 2).

The combined hydrograph of flows from the Assiniboine (1995 flood) and the Red River (1997 flood) is shown in Figure 7. The historic flood of 1826 was also simulated. Floodway was used up to its maximum capacity while simulating both flooding events. The building and infrastructure damages were calculated for municipality of Rithchot (Ste. Agathe town included). The damage figures are shown in Table 3.

Table 1. Flood management with existing and revised operating rules for selected flood events

Flood Year	Operating Rules	Spill	Res. Full (days)	Upstream Flooding (days)	D/stream Flooding (days)	Area Flooded (ha)
1974	Existing	Natural	101	4	11	630
	Revised	Natural	119	6	5	70
	Revised	Gated	125	1	0	0
1976	Existing	Natural	120	2	7	370
	Revised	Natural	158	0	0	0
	Revised	Gated	158	0	0	0
1979	Existing	Natural	106	5	19	1,067
	Revised	Natural	121	11	12	151
	Revised	Gated	129	0	0	0
1995	Existing	Natural	161	7	47	24,530
	Revised	Natural	193	5	38	21,537
	Revised	Gated	250	30	23	16,234

Table 2. Impacts on flooding by changing reservoir levels at the beginning of 1976 flood season without using gated spillway

Initial Res. Level (m)	Reservoir Full (days)	Upstream Flooding (days)	Downstream Flooding (days)	Total Area Flooded (ha)
422.2	163	0	0	0
425.2	174	12	17	4,790
428.3	195	13	26	20,160
429.2	195	13	31	21,030

Table 3. Damages caused by 1997 and 1826 flood events

Building Categories	Damages for 1997 Flood	Damages for 1826 Flood
Residential Buildings	40,136,100	143,256,000
Agricultural Buildings	1,465,200	8,650,000
Commercial/Industrial	13,650,000	22,274,150

Infrastructure	12,283,000	19,759,300
Total Damages	**67,534,600**	**193,939,450**

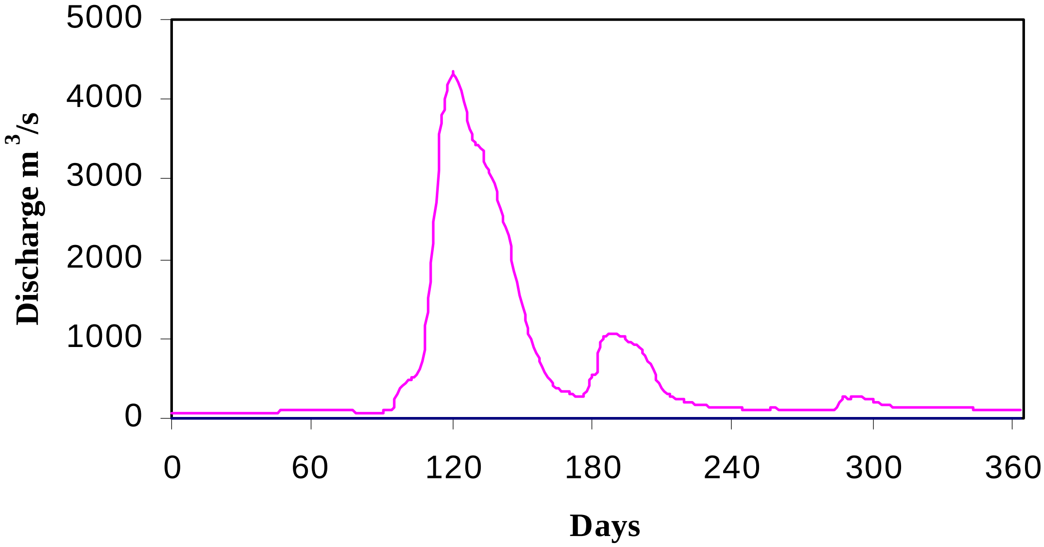


Fig 7. Combined hydrograph of 1995 flood in the Assiniboine and 1997 flood in Red in Winnipeg City

While simulating 1826 flood it was found that the additional floodway capacity required to protect the city of Winnipeg for this type of flood event would be about 1800 m^3/s.

Summary of Results

System Dynamics proved to be a very time efficient, user friendly and appropriate approach for modeling the operation of flood control structures. The simulation of the reservoir operation verified that with the revised operating rules the capability of the Shellmouth Reservoir for flood management can be improved. For four out of five largest historic floods, the reservoir was operated without causing any significant downstream or upstream flooding. Due to revision of operating rules the contribution of the Assiniboine River towards the flooding of the Winnipeg City is negligible. Number of days when reservoir is full or at the minimum level is very sensitive to reservoir outflows, especially over the falling limb of the flood hydrograph. Reservoir levels during the flood, upstream and downstream flooded area, and duration of flooding are sensitive to reservoir level at the beginning of the flood season. Simulation of the Shellmouth reservoir operation, considering both gated and unregulated spillway options, suggests that installation of gates on the spillway will improve the flood management capacity of the reservoir, especially for large floods. Moreover, the damages in the Red River Basin are very sensitive to water levels in the floodplain.

Conclusions

The research reported in this paper focused on the analysis of flood management policies using the SD approach. For the Shellmouth Reservoir operating rules were revised to minimize flooding for high flow/flood years. Impacts on flood management capacity of the reservoir were explored by simulating gated spillway in addition to the existing unregulated spillway. Alternative operating rules were explored by changing the reservoir storage allocation, reservoir levels at the beginning of flood season and the reservoir outflows. Operation of the Red River floodway was simulated too. Damages were estimated for St. Agathe area due to 1997 and 1826 flood events. The modeling work on economic impacts of flood management policies is complete. However, the work on social aspects of flood management, especially public response to flood warning and people's perception of risk with special relevance to evacuation planning is in progress.

The proposed SD based simulation approach is a valuable alternative to conventional simulation techniques. The increased speed of model development, the ease of model structure modification, ability to perform sensitivity analysis and the effective communication of model results are the main strengths of SD based simulation approach. However, one limitation is the need for simplification of flood routing as compared to sophisticated hydrodynamic models (Ahmad and Simonovic, 2000). Currently, single water level value is used to calculate damages in the floodplain. This is an approximation that may be addressed by using a cell based modeling approach with damages calculated in each cell with a different value of water level.

Because of ease of construction and modification, SD simulation environments facilitate rapid prototyping and greatly reduce programming effort. Modeling effort can be directed to important tasks such as system conceptualization, data collection, gaining input from system operators and involving stakeholders. The Shellmouth Reservoir and the Red River floodway simulation model can be fine-tuned easily in the light of operating experience, or with the help of insight provided by an expert. The SD approach offers a way for operators to participate in the model building process, thus increasing their trust in the model. The operator's feedback provides direction for follow-up simulations and modifications of the model structure.

The entire modeling process is open, interactive and transparent. The model is easy to expand and modify in terms of its internal structure and the amount, type, and resolution of data used. Modifications, in both structure and values of parameters, can be made easily as new information that can affect the model becomes available. The model can then be re-run, the results analyzed and the model improved as necessary. Numerous simulation scenarios, in addition to what has been demonstrated in this study, can be tested using the existing framework. As the current model provides information on extent and duration of flooding, another sector can be added to calculate damage to crops or economic losses due to lost opportunity of seeding. The model can be extended from a single multipurpose reservoir to a system of reservoirs and other flood control structures may be added in the model. Currently, work is in progress to model the social impacts of flood management process.

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